



## Detectors for Neutrino Physics at the First Muon Collider

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April 1998

*Published Proceedings of the Workshop on Physics at the First Muon Collider and at the Front End of a Muon Collider, Fermilab, Batavia, Illinois, November 6-9, 1997*

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# Detectors for Neutrino Physics at the First Muon Collider

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**Abstract.** We consider possible detector designs for short-baseline neutrino experiments using neutrino beams produced at the First Muon Collider complex. The high fluxes available at the muon collider make possible high statistics deep-inelastic scattering neutrino experiments with a low-mass target. A design of a low-energy neutrino oscillation experiment on the “tabletop” scale is also discussed.

## INTRODUCTION

This contribution considers the problem of constructing detectors appropriate for doing short-baseline neutrino physics at the First Muon Collider complex. The physics motivations for these detectors are discussed elsewhere in these proceedings [1]. Since the proposed experiments are short-baseline, the physics being considered is primarily the high-energy physics of neutrino-nucleon deep-inelastic scattering; however, the final section of the paper considers an oscillation experiment possible with the lowest energy neutrino beam.

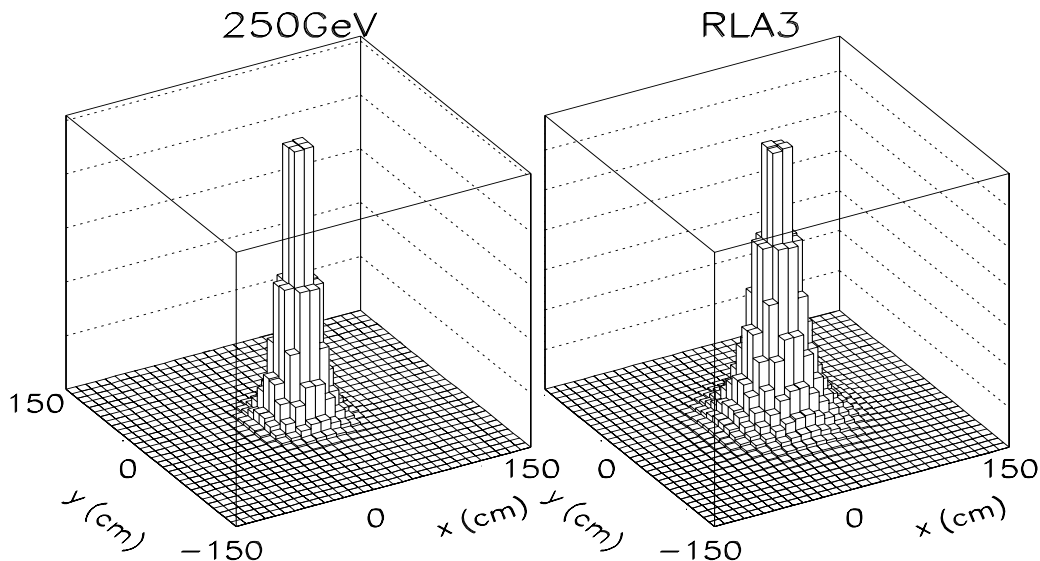
## NEUTRINO BEAMS AT THE MUON COLLIDER COMPLEX

The muon collider is expected to use a series of recirculating linacs to accelerate the muons before injection into a collider ring. Any segment along the muon’s trajectory that is straight will necessarily create a collimated neutrino beam with an angular divergence of approximately  $1/\gamma_\mu$ . The recirculating linacs (RLAs) will have  $\mathcal{O}(300\text{m})$  in which acceleration takes place, and the interaction points in the collider rings will also have 5-10m straight sections.

We wrote a simple Monte Carlo of the muon collider straight sections to predict fluxes, based on the workshop muon accelerator parameters. We used the  $\mu^-$  beam, and assumed the beam polarization and divergence were zero. Fluxes were predicted far downstream of each straight section in order to allow for shielding. We considered only a “dumb” shield option in which

Experiment:	RLA1	RLA2	RLA3	Med Eng	Top	High Eng
Max Muon Energy (GeV)	10	70	250	100	175	250
Distance (m)	23.3	163	582	233	408	582
50% $\nu$ 's within radius	25 cm	30 cm	25 cm	15 cm	15 cm	15 cm
90% $\nu$ 's within radius	75 cm	75 cm	60 cm	40 cm	40 cm	40 cm
$\nu$ DIS events, ( $\times 10^6$ ), $r < 10cm$	n/a	0.038	0.11	0.13	0.21	0.34
$\nu$ DIS events, ( $\times 10^6$ ), $r < 150cm$	n/a	0.49	0.92	0.54	0.99	1.34

**TABLE 1.** For each straight section in the RLAs and for several different collider scenarios, the maximum muon energy, the required shielding distance, the  $\nu$  beam size and the  $\nu$  DIS events in Millions per g/cm<sup>2</sup>/yr are shown.



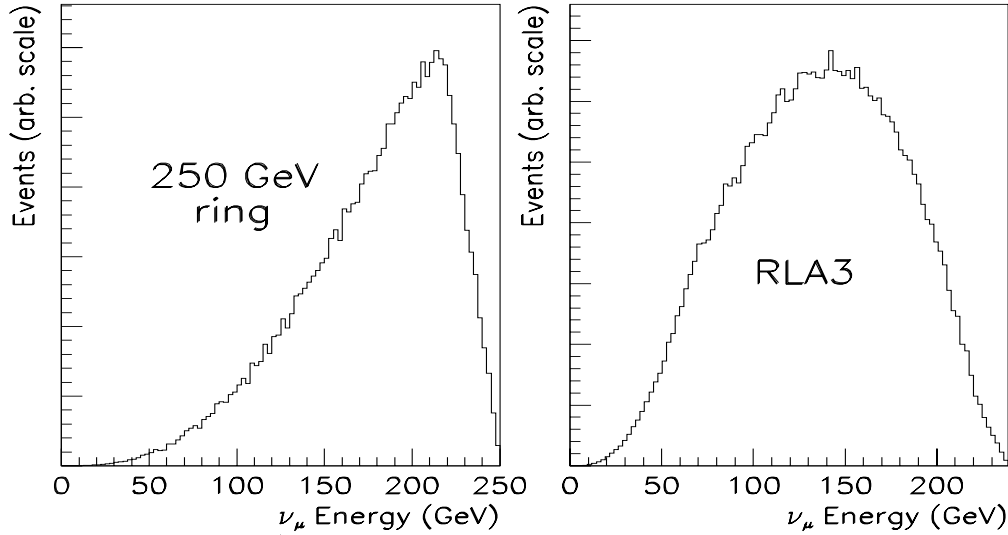
**FIGURE 1.** Event illuminations in two possible neutrino experiments

sufficient concrete shielding to range out the muons from the primary muon beam was used. Table 1 gives a table of the distances of a proposed experiment downstream of each straight section in the RLAs and collider.

## Predicted Neutrino Fluxes

As shown in Table 1, the beam is relatively small at all energies (since we have chosen a baseline which is proportional to energy due to shielding concerns). Figure 1 shows a typical event illumination for two possible neutrino experiments: one downstream of RLA3, and one downstream of the 250GeV collider ring's straight section.

Figure 2 shows the neutrino energy spectra reaching a 10cm radius neutrino target downstream of RLA3, and also for the same target downstream of a 250 GeV collider ring straight section. Unlike neutrino beams made by



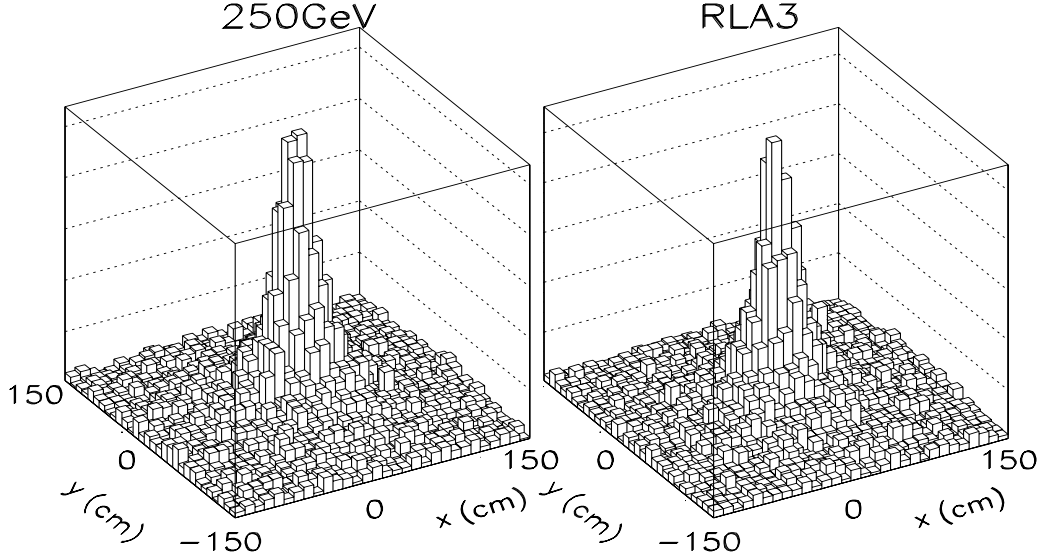
**FIGURE 2.** Neutrino Energy Spectra for two experiments, each with a target of 10 cm radius: one downstream of the 250 GeV collider ring straight section and one downstream of RLA3. The broader distribution from RLA3 is an artifact of the energy ramp in RLA3; turn-by-turn, the spectra have a similar shape.

decays of hadrons, the energy spectra will be well known from the accelerator parameters at a muon collider. This will make the difficulties of separating flux and cross-section relatively trivial and the flux endpoint will provide an important detector calibration.

## Muon Flux at Neutrino Experiments

The shielding necessary to protect a neutrino experiment from primary muons will produce large numbers of muon neutrino DIS interactions some of which will produce muons in the neutrino detector. The Monte Carlo simulation described earlier contained muon production and propagation in shielding to predict the size of this background. Figure 3 shows the surprisingly peaked muon illumination at the detector for experiments downstream of RLA3 and the 250 GeV collider using these assumptions.

The critical number for an experiment is the maximum number of muons arriving at the detector for a single turn in the accelerator. This flux is listed in Table 2. The background for a detector measuring  $100\text{cm}^2$  is always  $\leq 0.06$  muons/turn and is therefore not a problem. However, for large detectors downstream of the recirculating linacs more complicated shielding would be necessary. One option would be to have magnetized shielding followed by an empty volume which could bend any produced muons away from the neutrino target. Another possibility could be to use shielding heavier than concrete



**FIGURE 3.** Maximum background muon illuminations in one turn for two possible neutrino experiments

Experiment:	RLA1	RLA2	RLA3	Med Eng	Top	High Eng
Muons/Turn	0.015	0.06	0.4	0.0015	0.0025	0.0035
Muons in center $100\text{cm}^2$	0.0028	0.017	0.081	0.00014	0.00024	0.00033
$\nu_\mu$ DIS events/Turn	0.05	0.07	0.27	0.0015	0.0015	0.002

**TABLE 2.** Per pulse interaction rates in a  $40\text{ cm} \times 40\text{ cm}$   $10\lambda_0$  steel sampling calorimeter and muon filter located downstream of a “dumb” muon filter which ranges out the direct beam muons.

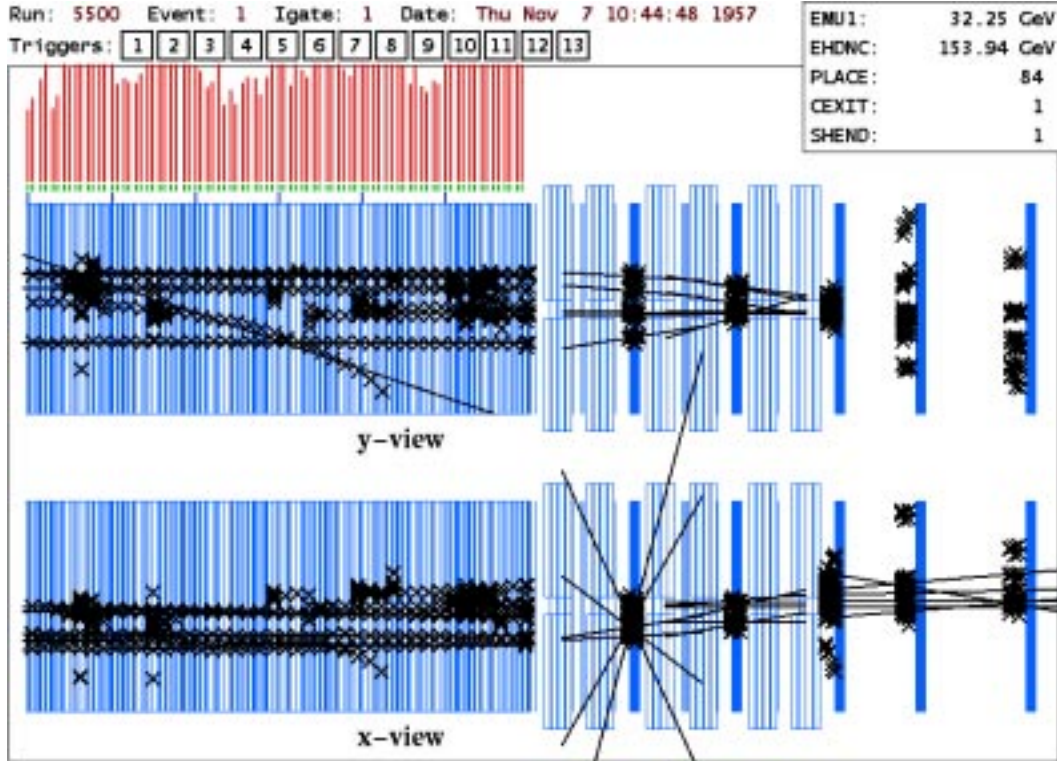
again with a long empty volume just upstream of a large detector to allow the muons to scatter away from the detector acceptance.

## HIGH MASS NEUTRINO TARGET

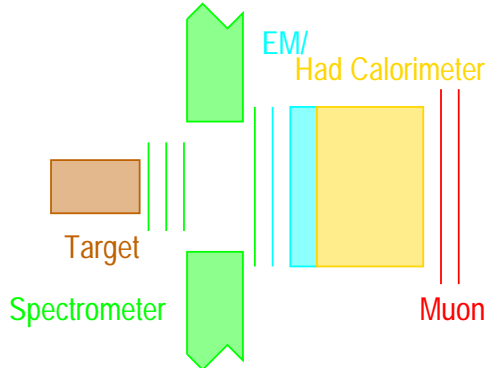
The fluxes detailed above represent improvements by 3 to 5 orders of magnitude over contemporary high energy neutrino beams<sup>1</sup>. It would therefore be possible to run an experiment with conventional high-mass sampling target-calorimeters and observe perhaps  $10^{11}$  events per year in previously explored energy regimes.

However, sampling calorimeters would have some difficulties in the FMC environment. High mass sampling calorimeters are only designed for the de-

<sup>1)</sup> The NuTeV SSQT had an interaction rate of  $\mathcal{O}(10)$  events/kg/yr with a mean energy of 120 GeV [2]; beams at the CERN PS used by NOMAD and CHORUS had a mean energy of 35 GeV and observed  $\mathcal{O}(100)$  events/kg/yr [3].



**FIGURE 4.** An extreme Monte Carlo event in the NuTeV detector, placed 600 meters downstream of RLA3. This event contains six neutrino interactions and three muons produced in upstream shielding from a single turn of the muon beam. This number of muons would be very unlikely, but the number of neutrino interactions is below average in the NuTeV detector



**FIGURE 5.** A schematic of an FMC neutrino detector in the style of conventional fixed target detectors.

tection of  $\nu_\mu$  or  $\bar{\nu}_\mu$  since  $\nu_e$  and  $\bar{\nu}_e$  events are difficult to separate from neutral current interactions of other neutrino species, especially when the final state lepton has a low fraction of the initial neutrino energy. Therefore, unless the muon beam polarity of the FMC were reversible, only neutrinos or anti-neutrinos could be observed in a single detector. Furthermore, high mass, sparsely instrumented detectors are sensitive to pile-up. As per pulse event rates in Table 2 show, this is a particular concern downstream of the high-energy recirculating linacs where the beam is concentrated in time in a relatively small number of turns. Figure 4 shows an extreme illustration of the difficulties of dealing with pile-up in a sample-calorimeter.

Assuming these difficulties could somehow be overcome, it is also unclear what the novel physics available from  $10^{11}$  neutrino interactions in dense material would be. In general, precision measurements from neutrinos are systematics limited in such detectors<sup>2</sup> and searches for rare phenomena are background limited.

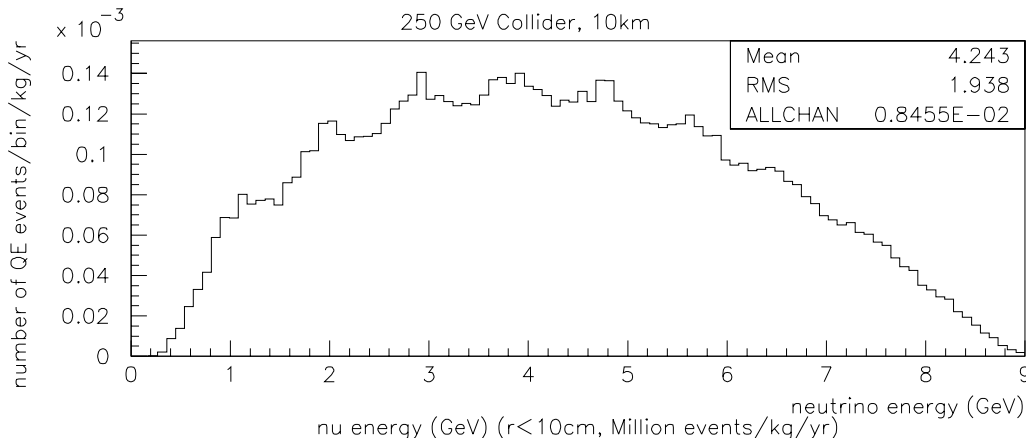
## CONVENTIONAL FIXED-TARGET GEOMETRY

Probably more interesting than the above detector technology would be one where the target is small enough to vary its composition for studies of nuclear effects on nucleon structure or even spin physics in neutrino deep inelastic scattering. This is possible in a geometry more closely resembling traditional fixed-target experiments: target, followed by spectrometry and calorimetry and muon identification as shown in Figure 5. The problems of tracking, particle-ID and calorimetry in such detectors are well-known and will not be discussed here. Such a detector would presumably be able to identify the outgoing lepton in charged-current events, possibly with TRDs in the downstream tracking providing enhanced identification. This detector

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<sup>2)</sup> For example, the measurements of  $\alpha_S$  [4] and  $\sin^2 \theta_W$  [5] in the CCFR experiment





**FIGURE 6.** Energy spectrum of quasi-elastic  $\nu_\mu$  events downstream of RLA1.

would be able to tag the production of charmed particles by observing high momentum final state leptons, and with a sufficiently fine-grained upstream tracker, charmed final state particles could be tagged *via* detached vertices [6]. Physics goals of an experiment using this detector are described elsewhere in these proceedings [1].

The most serious technical difficulties of such detectors is pile-up in the dense calorimetry and muon systems. A typical iron-scintillator sampling calorimeter/muon shield of  $10 \lambda_0$  (1.6 m of steel or  $13 \text{ kg/cm}^2$ ) would observe the per pulse background rates shown in Table 2. Background rates at the collider are probably manageable, but the background rates at the RLAs, particularly RLA3, could be difficult.

## A TABLE-TOP LOW ENERGY NEUTRINO DETECTOR

Another avenue that becomes possible with the FMC neutrino beams is searching for neutrino oscillations in a modest-sized experiment. Figure 6 shows the expected energy spectrum of quasi-elastic  $\nu_\mu$  events downstream of RLA1. In a water-density  $0.05 \text{ m}^3$  target, one would expect to observe approximately 0.4 Million events per year. This sets the scale for a truly “table-top” scale neutrino oscillation experiment.

With a flavor selected beam of  $\overline{\nu}_\mu$  and  $\nu_e$ , the simplest search experimentally<sup>3</sup> is for wrong-sign muon ( $\mu^-$ ) appearance. The primary backgrounds would come from mis-identifying the muon charge or from production of charged

<sup>3</sup>)  $e^+$  appearance is background-laden at these energies and  $\tau$  appearance, aside from being heavily suppressed by  $m_\tau$ , requires a more sophisticated detector.

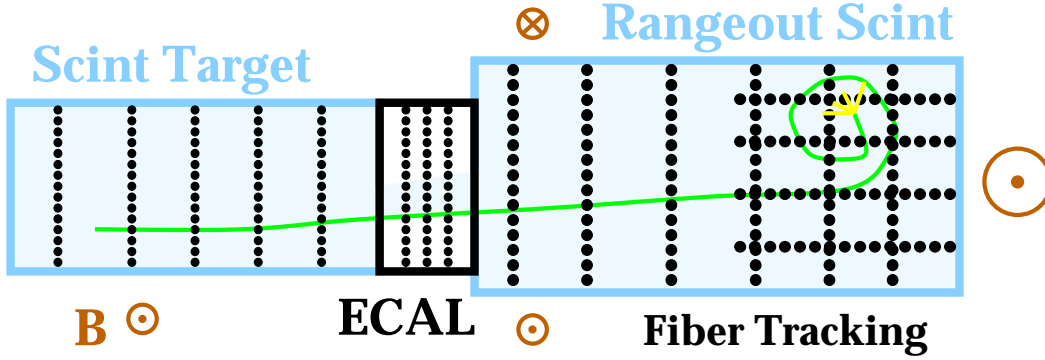


FIGURE 7. A table-top sized neutrino detector for that beam.

pions which could decay or be misidentified as muons. By conclusively identifying  $\mu$  charge in a spectrometer, tracking the particle from the point of appearance and observing its decay with a characteristic muon lifetime, these backgrounds could presumably be kept very low. A naive version of a detector designed for this measurement appears in Figure 7. With proper granularity of tracking and careful optimization of the magnetic field for a broad acceptance in momentum, even such a small scale detector could reach  $10^{-5}$  sensitivity if naive background estimations are correct.

## CONCLUSIONS

We have presented outlines of detector designs for short-baseline neutrino experiments at the first muon collider complex. This facility would make available neutrino beams of unprecedented intensity, and we argue that the best way to take advantage of this is to design novel detectors, such as small targets or “table-top” neutrino experiments to explore different aspects of neutrino scattering or neutrino oscillations than those studied in the past.

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